

# **Compression Strength of Composite Primary Structural Components**

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## **Final Report**

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## Introduction

Research conducted under NASA Grant NAG-1-537 focussed on the response and failure of advanced composite material structures for application to aircraft. Both experimental and analytical methods were utilized to study the fundamental mechanics of the response and failure of selected structural components subjected to quasi-static loads. Most of the structural components studied were thin-walled elements subject to compression, such that they exhibited buckling and postbuckling responses prior to catastrophic failure. Consequently, the analyses were geometrically nonlinear.

Structural components studied were dropped-ply laminated plates, stiffener crippling, pressure pillow of orthogonally stiffened cylindrical shells, axisymmetric response of pressure domes, and the static crush of semi-circular frames. Failure of these components motivated analytical studies on an interlaminar stress postprocessor for plate and shell finite element computer codes, and global/local modeling strategies in finite element modeling. These activities are summarized in the following section. References to literature published under the grant are listed on pages 5 to 10 by a letter followed by a number under the categories of journal publications, conference publications, presentations, and reports. These references are indicated in the text by their letter and number as a superscript.

## Research Activities

**Dropped-ply laminated plates** Dropping plies is a method of tailoring the stiffness of laminates, and dropping plies is common in airplane structures. For example, plies are dropped from root to tip in wing skins at discrete locations along the span. Dropped plies results in an abrupt thickness taper. The abrupt thickness taper can reduce the strength of a dropped-ply laminate below the strength of its thin section alone. The mode of failure initiation is usually delamination at the ply termination. Curry, et al.<sup>J2, C2, P2, R1</sup> conducted experiments on dropped-ply laminated plates fabricated from graphite-epoxy tape in tension and compression, and found that the compression strength reduction due to the dropped plies is larger than the tensile strength reduction. Curry, et al.<sup>J2, C2, P2, R1</sup> analyzed the dropped-ply specimens that exhibited a linear response to the first major failure event, and corroborated that delamination at the drop ply site is the critical mode. The increase in stiffness along the load path from the thin to thick section correlated very closely with the reduction in strength. Dropped-ply compression specimens tested by Curry, et al., that delaminated at the ply termination in postbuckling were analyzed by Dávila and Johnson<sup>J3, C7, P5</sup>, and Johnson and Dávila<sup>C5</sup>. A  $[90_2]$  dropped-ply laminate tested in compression by Curry failed in postbuckling near a nodal line in the thin section and not at the ply termination. The  $[90_2]$  dropped-ply laminate was termed the soft insert, since the stiffness along the load path did not change significantly from the thin to thick section. Barlas and Johnson<sup>R7</sup> analyzed the nonlinear response of this specimen with the soft insert and determined that the interlaminar shear stress component tangent to free edge is responsible for delamination in the 45/-45 interface.

**Stiffener crippling** Stiffened aircraft panels subject to compression collapse in postbuckling when the stiffener cross section exhibits a local distortion, which is called local crippling in the aircraft structures literature. Tests and analyses of the response and failure of graphite-epoxy stiff-

ener sections were conducted by Bonanni, et al.<sup>J1, C3, P3, R2</sup>. Some of these crippling specimens failed by delamination at the free edges of the flanges. Barlas and Johnson<sup>C9, R7</sup> used a global/local finite element model combined with a variable complexity modeling strategy to analyze free edge delamination as a mode of crippling in graphite-epoxy stiffeners. It was determined that nodal line lines and inflection points in the out-of-plane displacement at the free edge of the flange are delamination critical sites. The interlaminar shear stress tangent to the free edge is an extremum at the nodal lines and inflection points.

**Interlaminar stress postprocessor** In the stiffener crippling research, many test specimens failed during their geometrically nonlinear response by delamination. The analyses conducted at the time of this research used the shell finite element code STAGS. By its inherent assumptions, shell theory neglects stress components in the thickness direction with respect to stress components in the in-plane directions. Hence, since delamination is caused by the stress components in the thickness direction, it was not possible to use STAGS results to predict delamination. A series of studies conducted by Bonanni, et al.<sup>R2</sup>, Johnson and Bonanni<sup>C4</sup>, Foster and Johnson<sup>R3</sup>, and Foster<sup>P7</sup> were undertaken to predict interlaminar stresses based on finite element solutions to plate and shell models. Formulas were derived for the thickness direction stresses in Ref. R2 by integrating the three-dimensional elasticity equilibrium equations in the thickness coordinate, and assuming that the in-plane stresses are distributed linearly in the thickness coordinate in each ply as predicted by plate theory. These formulas require displacement derivatives of the order  $2p$ , where  $p$  is the highest order derivative of the displacement in the strain energy functional. Derivatives of order  $2p$  are not represented in a finite element formulation. Interpolation of finite element data over a subdomain of elements using Fourier Series and Chebyshev polynomials was attempted to estimate derivatives of order  $2p$ . Also, we implemented a spectral method that used a collocation solution to the governing Euler equations of plate theory over subdomain subject to essential boundary condition data obtained from the finite element solution. It was found that finite element displacements must have an accuracy of six significant figures to get less than a 10% error in the forth derivative of the out-of-plane displacement (the  $2p$  derivative in this case) using Chebyshev interpolation. So interpolation over a subdomain is not likely to be reliable method to estimate interlaminar stresses. Also, it was found that the spectral method and the interpolation formulas exhibited the same degree of sensitivity to the sampled finite element data in regard to computation of order  $2p$  derivatives. Hence, the extra effort to compute the spectral solution was not warranted.

**Initial postbuckling of unsymmetrically laminated plates** Haftka and Johnson<sup>C6, P6</sup> presented an analysis of the initial postbuckling response of unsymmetrically laminated, cross-ply, rectangular plates. Unsymmetrically laminated plates exhibit asymmetric bifurcation buckling behavior from their flat, pre-buckled equilibrium configuration. Special in-plane load distributions and a special reference plane are necessary to achieve a pre-buckling response for which the unsymmetrically laminate plate remains flat. Johnson and Haftka<sup>C8, P9</sup> extended the analysis to include off-axis plies and to enforce straight edges in postbuckling. There is only a mild decrease in load after buckling for the plates examined in these studies.

**Pressure pillowing of an orthogonally stiffened cylindrical shell** Johnson and Rastogi<sup>J4, C10, C11, P10, P12, P13, R8</sup> used a Fourier analysis determine the response of a repeating unit of a frame-and-stringer stiffened cylindrical shell subject to internal pressure. The stringer is modeled as a

beam-column, and the frame is modeled as a ring. The stiffeners prevent the shell, or skin, from radial expansion in the vicinity of the stiffeners, and this deformation pattern of the skin is called "pillowing". Skin pillowing is reduced in a geometrically nonlinear analysis with respect to linear analysis. The Fourier Series for interacting normal load intensities between the stiffeners and the shell at stiffener junction does not converge in either the linear or geometrically nonlinear analysis. However, the radial resultant of the interacting normal load distributions does converge with a small number of terms retained in the series. This radial resultant at stiffener junction increases in magnitude in geometrically nonlinear analysis relative to the linear analysis. Hence, the stiffeners resist an increased portion of internal pressure compared to the shell in the nonlinear analysis with respect to the linear analysis.

Rastogi and Johnson<sup>J5, C12, P14</sup> extended the linear analysis to include an asymmetrical section ring, as the asymmetric open section frame is common in a fuselage structure. The analysis included the warping of the ring's cross section due to torsion. Four different models are compared: classical theory with and without warping, and a transverse shear deformation theory with and without warping. Inclusion of transverse shear deformations increases joint flexibility by decoupling the ring's torsional rotation from stringer's bending rotation. Warping deformation of the ring accounts for essentially all of the torque carried by the ring with the St. Venant portion of the torque being negligible. Shell normal displacement and in-plane normal strains are not effected very much by the different theories.

**Axisymmetric response of composite pressure domes** On a large transport aircraft the fuselage is closed at the aft end by a dome-shaped pressure bulkhead. There is an abrupt change in curvature at the joint between the fuselage and the dome, which induces a stress raiser. The objective of this research is to use dome geometry and laminated composite wall stiffnesses to minimized the stress raiser at the joint between the cabin shell and aft pressure bulkhead. Steinbrink and Johnson<sup>C13</sup> derived the governing equations for the linear response of axisymmetric, composite, doubly curved shells subject to internal pressure in first-order state vector form. The state vector form has the advantage of computing all of the shell resultants and their derivatives as part of the solution procedure. Hence, the higher order derivatives required in the interlaminar stress formulas are obtained directly, enabling evaluation of the delamination mode of failure. The linear state vector equations are solved by direct numerical integration using a multiple shooting technique. The geometrically nonlinear governing equations for the axisymmetric response of the composite dome under hydrostatic pressure were derived as well, and their numerical solution is in progress.

**Solid-to-shell transition finite element** The research on failure initiation by delamination of dropped-ply laminates and composite stiffener crippling requires the computation of interlaminar stresses from a finite element solution to a plate or shell model. As discussed above, efforts to develop a postprocessor to compute interlaminar stresses from a finite element solution were not particularly encouraging. An alternative method is to use a finite element model that contains both two-dimensional plate and shell elements and three-dimensional solid elements. The solid elements are located in the regions in which interlaminar stress raisers occur; for example, at ply terminations and at free edges, while plate/shell elements are used everywhere else. A model containing all solid elements would result in a prohibitively large number of equations to solve, and is not warranted based on the mechanics of the response. Geometrically nonlinear analyses required in postbuckling add to the computational burden. Consequently a finite element model containing both shell and solid elements is attractive. However, shell and solid elements are not

compatible, so that transition elements need to be developed to connect the shell and solid elements, or multipoint constraints can be used to implement shell and solid elements in one model. Transition elements are easier to implement by the user of the code, particularly for large complex structures. Dávila and Johnson<sup>R4, R5, R6</sup> developed a solid-to-shell transition element that connects shell and solid elements for laminated wall construction by degenerating a twenty-noded solid element using the kinematic constraints of shell theory. The shell nodes of the transition element do not have to be situated on the element itself, which permits stacking of the transition elements through the thickness of the laminate, and connecting all of them to one shell element. Dávila and Johnson<sup>J3, C7</sup> used this transition element to investigate delamination at the ply termination site in postbuckled, dropped-ply laminates. Barlas and Johnson<sup>R7</sup> used this transition element in the postbuckled dropped-ply laminate containing the soft [90<sub>2</sub>] insert which failed by transverse shear near a nodal line in the thin section of the plate. Also, Barlas and Johnson<sup>C9, P11</sup> used this transition element to investigate free edge delamination of the flange of a postbuckled stiffener section. Schultz<sup>P18</sup> improved the transition element by relaxing the inextensional normal assumption of shell theory while retaining kinematic continuity of the average out-of-plane displacement between the shell and transition element.

**Static crush tests of optimized semi-circular composite frames** Vertical drop testing of transport aircraft fuselage sections indicate that the frames play a major role in the process of absorbing the impact energy in the crushing of the substructure below the main passenger deck. Subsequent static crush tests of scaled frames fabricated from graphite-epoxy tape show that they tend to absorb less energy than their aluminum counterparts due to the brittle-type failure modes of the composite compared to failure by ductile yielding of the aluminum. A mathematical model developed to optimize open section curved composite frames under static crush loading for improved energy absorption is used to design previously fabricated graphite-epoxy frames not optimized for energy absorption. Flanges were resized on three of these previously fabricated semicircular, I-section, frames. Static test results of the redesigned frames are compared to test results of the nominally equivalent original frames. The test results from the redesigned frames show an improved energy absorption relative to their original counterparts, and that the mathematical model predicts the correct sequence and location of failure events. However, the mathematical model did not predict the magnitudes of the force and displacement at the first major failure event that occurred in the test. See the paper by Perez, Johnson, and Boitnott<sup>C14, P16</sup>

## Publications

### Journal Papers

- J1. Bonanni, David L., Johnson, Eric R., and Starnes, James H., Jr., "Local Crippling of Thin-Walled Graphite-Epoxy Stiffeners", **AIAA Journal**, Vol. 29., No. 11, November 1991, pp. 1951-1959.
- J2. Curry, James H., Johnson, Eric R., and Starnes, James H., Jr., "Effect of Dropped Plies on the Strength of Graphite-Epoxy Laminates," **AIAA Journal**, Vol. 30, No.2, February 1992, pp. 449-456.
- J3. Dávila, Carlos G., and Johnson, Eric. R., "Analysis of Delamination Initiation in Postbuckled Dropped-Ply Laminates," **AIAA Journal**, Vol. 31, No. 4, April 1993, pp. 721 - 727.
- J4. Johnson, E.R., and Rastogi, N., "Interacting Loads in an Orthogonally Stiffened Composite Cylindrical Shell," **AIAA Journal**, Vol. 33, No.7, July, 1995, pp. 1319-1326.
- J5. Rastogi, N., and Johnson, E. R., "Analysis of an Internally Pressurized Orthogonally Stiffened Cylindrical Shell with an Asymmetrical Section Ring," **Mechanics of Composite Materials and Structures**, Vol. 3, No.1, March 1996, pp. 29-64.

### Conference Papers

- C1. Lo, Patrick K-L, and Johnson Eric. R., "One-Dimensional Analysis of Filamentary Composite Beam Columns with Thin-Walled Open Sections," in **Composites '86: Recent Advances in Japan and the United States**, K. Kawata, S. Umekawa & A. Kobayashi, Eds., Proceedings of the Third Japan-U.S. Conference on Composite Materials, Japan Society For Composite Materials, 1986, pp. 405-414. (Supported in part by NASA Grant NAG-1-343.)
- C2. Curry, James M., Johnson, Eric R., and Starnes, James H., Jr., "Effect of Dropped Plies on the Strength of Graphite-Epoxy Laminates," AIAA Paper No. 87-0874, in the proceedings of the *AIAA/ASME/ASCE/AHS 28th Structures, Structural Dynamics and Materials Conference*, Part 1, April 6-8, 1987, Monterey, California, pp. 737-747.
- C3. Bonanni, David L., Johnson, Eric., R., and Starnes, James H., Jr., "Local Crippling of Thin-Walled Graphite-Epoxy Stiffeners," AIAA Paper No. 88-2251, in the proceedings of the *AIAA/ASME/ASCE/AHS 29th Structures, Structural Dynamics and Materials Conference*, Part 1, April 18-20, 1988, Williamsburg, Virginia, pp. 313-323. (Supported in part by NASA Grant NAG-1-343.)
- C4. Johnson, E. R., and Bonanni, D. L., "Order 2p Derivatives from p-Differentiable Finite Element Solutions by a Spectral Method," in *CAD/CAM, Robotics and Factories of the Future*, Vol. 1, Birendra Prasad, Ed., Springer-Verlag, Berlin, 1989, pp. 134-138.
- C5. Johnson, Eric R., and Dávila, Carlos G., "Compression Buckling of Thick Orthotropic

Plates with a Step Thickness Change,” in the *Proceedings of the Twelfth Canadian Congress of Applied Mechanics*, Carleton University, Ottawa, Canada, M. A. Erki and J. Kirkhope, Eds., Vol. 1, 28 May - 2 June, 1989, pp. 140 & 141.

- C6. Haftka, Raphael T., and Johnson, Eric R., “Initial Postbuckling Response of an Unsymmetrically Laminated Rectangular Plate,” in the Proceedings of the *Eighth DOD/NASA/FAA Conference on Fibrous Composites in Structural Design*, November 28-30, 1989, Norfolk, Virginia, NASA Conference Publication 3087, Part 2, 1990, pp. 609-623. (Supported in part by NASA Grant NAG-1-168.)
- C7. Dávila, Carlos G., and Johnson, Eric R., “Analysis for Delamination Initiation in Postbuckled Dropped-ply Laminates,” AIAA Paper No. 92-2226, in the proceedings of *The 33rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Part 1, April 13-15, 1992, Dallas Texas, pp. 29-39.
- C8. Johnson, Eric R., and Haftka, Raphael T., “Initial Postbuckling Response of Anisotropic Laminated Rectangular Plates,” AIAA Paper No. 92-2284, in the proceedings of *The 33rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Part 1, April 13-15, 1992, Dallas Texas, pp. 241-263. (Supported in part by NASA Grant NAG-1-168.)
- C9. Johnson, Eric R., and F. Aylin Barlas, “Interlaminar Stress Concentration in Postbuckled Open section Stiffeners,” in *Mechanics of Composite Materials—Nonlinear Effects*, edited by M. W. Hyer, AMD-Vol. 159, American Society of Mechanical Engineers, New York, NY, 1993, pp. 19-28.
- C10. Johnson, Eric R., and Rastogi, Naveen, “Interacting Loads in an Orthogonally Stiffened Composite Cylindrical Shell,” Proceedings of Center for Adhesive and Sealant Science and Center for Composite Materials and Structures, Program Review, Donaldson Brown Hotel and Conference Center, Virginia Polytechnic Institute and State University, Blacksburg Virginia, October 3-5, 1993, pp. II.M.1 - II.M.15.
- C11. Johnson, E. R., and Rastogi, N., “Interacting Loads in an Orthogonally Stiffened Composite Cylindrical Shell”, *Proceedings of the AIAA/ASME/ASCE/AHS/ASC 35th Structures, Structural Dynamics and Materials Conference* (Hilton Head SC), Part 5, AIAA, Washington, DC, April, 1994, pp. 2607 - 2620.
- C12. Rastogi, N., and Johnson, E.R., “Analysis of an Internally Pressurized Orthogonally Stiffened Cylindrical Shell with an Asymmetrical Section Ring,” Proceedings of *The 36th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, (New Orleans, LA, April 10-12, 1995), Part 3, AIAA, Washington, DC, pp. 1734-1759 (AIAA Paper No. 95-1368).
- C13. Steinbrink, S., and Johnson, E.R., “Analysis of Axisymmetric Composite Pressure Domes by the Multiple Shooting Method,” Proceedings of *The 38th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, (Kissimmee, FL, April 7-10, 1997), American Institute of Aeronautics and Astronautics, Reston, VA, Part 4, 1977, pp.

2844-2857 (AIAA Paper No. 97-1366).

- C14. Pérez, J.G., Johnson, E.R., and Boitnott, R.L., "Design and Test of Semicircular Composite Frames Optimized for Crashworthiness," Proceedings of *The 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, (Long Beach, CA, April 20-23, 1998), American Institute of Aeronautics and Astronautics, Reston, VA, 1988, Part 1, pp. 27-38 (AIAA Paper No. 98-1703).
- C15. Johnson, E.R., and Rastogi, N.R., "Effective Hygrothermal Expansion Coefficients for Thick Multilayered Bodies," Proceedings of *The 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, (Long Beach, CA, April 20-23, 1998), American Institute of Aeronautics and Astronautics, Reston, VA, 1988, pp. 1005-1022 (AIAA Paper No. 98-1814).

### **Presentations**

(Speaker indicated by boldface font.)

- P1. Lo, Patrick K-L, and **Johnson Eric. R.**, "One-Dimensional Analysis of Filamentary Composite Beam Columns with Thin-Walled Open Sections," in Session 10 Compression/Shear, The Third Japan-U.S. Conference on Composite Materials, June 23-25, 1986, Science University of Tokyo, Kagurazaka, Tokyo, Japan.
- P2. **Curry, James M.**, Johnson, Eric R., and Starnes, James H., Jr., "Effect of Dropped Plies on the Strength of Graphite-Epoxy Laminates," at the *AIAA/ASME/ASCE/AHS 28th Structures, Structural Dynamics and Materials Conference*, April 6-8, 1987, Monterey, California.
- P3. **Bonanni, David L.**, Johnson, Eric., R., and Starnes, James H., Jr., "Local Crippling of Thin-Walled Graphite-Epoxy Stiffeners," at the *AIAA/ASME/ASCE/AHS 29th Structures, Structural Dynamics and Materials Conference*, April 18-20, 1988, Williamsburg, Virginia.
- P4. **Johnson, E. R.**, and Bonanni, D. L., "Order 2p Derivatives from p-Differentiable Finite Element Solutions by a Spectral Method," at the *3rd International Conference on CAD/CAM Robotics and Factories of the Future (CARS & FOF '88)*, Southfield, Michigan, August 14-17, 1988.
- P5. Johnson, Eric R., and **Dávila, Carlos G.**, "Compression Buckling of Thick Orthotropic Plates with a Step Thickness Change," Special Session: Mechanics of Laminated Structures, at the *Twelfth Canadian Congress of Applied Mechanics*, Carleton University, Ottawa, Canada, 28 May - 2 June, 1989.
- P6. Haftka, Raphael T., and **Johnson, Eric R.**, "Initial Postbuckling Response of an Unsymmetrically Laminated Rectangular Plate," Methodology and Design Session, at the *Eighth DOD/NASA/FAA Conference on Fibrous Composites in Structural Design*, November 28-30, 1989, The Omni International Hotel, Norfolk, Virginia.



- P7. **Foster, John L.**, and Johnson, Eric R., "Computation of Interlaminar Stresses From Finite Element Solutions to Plate Theories," Session 35: Work in Progress II, at *The 32nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, April 8-10, 1991, Hyatt Regency Baltimore, Baltimore, Maryland.
- P8. **Dávila, Carlos G.**, and Johnson, Eric R., "Analysis for Delamination Initiation in Postbuckled Dropped-ply Laminates," Session 5: Damage Tolerance of Composites, at *The 33rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, April 13-15, 1992, Grand Kempinski Hotel, Dallas, Texas.
- P9. **Johnson, Eric R.**, and Haftka, Raphael T., "Initial Postbuckling Response of Anisotropic Laminated Rectangular Plates," Session 14: Buckling/Postbuckling of Plates and Stiffened Panels, at *The 33rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, April 13-15, 1992, Grand Kempinski Hotel, Dallas, Texas.
- P10. **Johnson, Eric R.**, and Rastogi, Naveen, "Interacting Loads in an Orthogonally Stiffened Composite Cylindrical Shell," presented in Session 25 — Work-in-Progress 1, at *The 34th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, April 19-21, 1993, Hyatt Regency, La Jolla, California.
- P11. **Barlas, F. Aylin**, and Johnson, Eric R., "Interlaminar Stress Concentration in Postbuckled Open-Section Stiffeners," presented in session *Nonlinear Structural Mechanics – 1*, Joint SES/ASME/ASCE Meeting, University of Virginia, Charlottesville, Virginia, June 6-9, 1993.
- P12. Johnson, Eric R., and **Rastogi, Naveen**, "Interacting Loads in an Orthogonally Stiffened Composite Cylindrical Shell," in Composite Session 3: Composite Structures – Analysis and Rehabilitation, Center for Adhesive and Sealant Science and Center for Composite Materials and Structures, Program Review, Donaldson Brown Hotel and Conference Center, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, October 3-5, 1993.
- P13. Johnson, E. R., and **Rastogi, N.**, "Interacting Loads in an Orthogonally Stiffened Composite Cylindrical Shell", *The AIAA/ASME/ASCE/AHS/ASC 35th Structures, Structural Dynamics and Materials Conference*, Session 53; Computational Structural Mechanics VI: Advanced Applications, April 18-20, 1994, Hyatt Regency Hilton Head, Hilton Head, South Carolina.
- P14. **Johnson, E.R.**, and Rastogi, N., "Influence of an Asymmetric Ring on the Modeling of an Orthogonally Stiffened Cylindrical Shell," International Conference on Composites Engineering, Sheraton Hotel Downtown, New Orleans, Louisiana, August 28 - 31, 1994 (Session 13f: Composite Structures 1).
- P15. **Steinbrink, S.**, and Johnson, E.R., "Analysis of Axisymmetric Composite Pressure Domes by the Multiple Shooting Method," Session 66-STR-21—Composite Beams, Plates and Shells I, *The 38th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Kissimmee, FL, April 7-10, 1997, American Institute of Aeronau-

tics and Astronautics, Reston, VA, (AIAA Paper No. 97-1366).

- P16. **Pérez, J.G.**, Johnson, E.R., and Boitnott, R.L., "Design and Test of Semicircular Composite Frames Optimized for Crashworthiness," Session 1– Failure & Damage Modeling I, *The 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Long Beach, CA, April 20-23, 1998, American Institute of Aeronautics and Astronautics, Reston, VA, (AIAA Paper No. 98-1703).
- P17. **Johnson, E.R.**, and Rastogi, N.R., "Effective Hygrothermal Expansion Coefficients for Thick Multilayered Bodies," Session 19–Material Properties and Behavior, *The 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Long Beach, CA, April 20-23, 1998, American Institute of Aeronautics and Astronautics, Reston, VA, (AIAA Paper No. 98-1814).
- P18. **Schultz, D.**, "A Shell-to-Solid Transition Finite Element for Improved Interlaminar Stress Response in Composite Laminates", Aeronautical and Aerospace Sciences Section, Virginia Academy of Science, 76th Annual Meeting, May 26-29, 1998, George Mason University, Fairfax, Virginia.

### Reports

- R1. Curry, J. M., Johnson, E. R., and Starnes, J. H., Jr., "Effect of Ply Drop-Offs on the Strength of Graphite-Epoxy Laminates," Center for Composite Materials and Structures, Virginia Polytechnic Institute. and State University., Blacksburg, VA 24061, Report. CCMS-86-07 and VPI-E-86-27, December 1986.
- R2. Bonanni, D. L., Johnson, E. R., and Starnes, J. H., Jr., "Local Buckling and Crippling of Composite Stiffener Sections," Center for Composite Materials and Structures, Virginia Polytechnic Institute. and State University., Blacksburg, VA 24061, Report. CCMS-88-08 and VPI-E-88-15, June 1988. (Supported in part by NASA Grant NAG-1-343.)
- R3. Foster, J. L., and Johnson, E. R., "Computation of Interlaminar Stresses From Finite Element Solutions to Plate Theory," Center for Composite Materials and Structures, Virginia Polytechnic Institute. and State University., Blacksburg, VA 24061, Report CCMS-91-10 and VPI-E-91-10, June 1991.
- R4. Dávila, Carlos G. and Johnson, Eric R., "The Computational Structural Mechanics Testbed: User's Manual for Transition Elements in Processor ES15," Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0203, August, 1991.
- R5. Dávila, C. G., and Johnson, E. R., "Delamination Initiation in Postbuckled Dropped-ply Laminates," Center for Composite Materials and Structures, Virginia Polytechnic Institute. and State University., Blacksburg, VA 24061, Report CCMS-91-24 and VPI-E-91-23, December 1991.
- R6. Dávila, Carlos G. and Johnson, Eric R., "The Computational Structural Mechanics Testbed:

User's Manual for Transition Elements in Processor ES16," Aerospace and Ocean Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0203, February 1992, (draft).

- R7. Barlas, F. Aylin, and Johnson, Eric R., "Variable Complexity Modeling of Postbuckled Stiffeners for Delamination Initiation," Center for Composite Materials and Structures, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, Report CCMS-93-11 and VPI-E-93-07, July 1993.
- R8. Johnson, E. R., and Rastogi, N., "Load Transfer in the Stiffener-to-Skin Joints of a Pressurized Fuselage," Center for Composite Materials and Structures, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, Report CCMS-95-04 and VPI-E-95-01, May 1995.

### **Students Supported by the Grant**

- 1. James M. Curry, Master of Science in Aerospace Engineering, May 1986.  
Thesis Title: Effect of Ply Drop-Offs on the Strength of Graphite-Epoxy Laminates  
Initial Employer: Rohr Industries, Inc., Chula Vista CA
- 2. David L. Bonanni, Master of Science in Aerospace Engineering, April 1988.  
Thesis Title: Local Crippling of Composite Stiffener Sections  
Initial Employer: David Taylor Research Center, Bethesda MD  
(Supported in part by NASA Grant NAG-1-343.)
- 3. John L. Foster, Master of Science in Aerospace Engineering, April 1991.  
Thesis Title: Computation of Interlaminar Stresses from Finite Element Solutions to Plate Theory  
Initial Employer: McDonnell Douglas Space Systems Co., Huntington Beach CA.
- 4. Carlos G. Dávila, Doctor of Philosophy in Aerospace Engineering, November 1991  
Dissertation Title: Delamination Initiation in Postbuckled Dropped-Ply Laminates  
Initial Position: National Research Council Resident Research Associate,  
NASA Langley Research Center, Hampton VA
- 5. F. Aylin Barlas, Master of Science in Aerospace Engineering, June 1993  
Thesis Title: Variable Complexity Modeling of Postbuckled Stiffeners for Delamination Initiation  
Initial Employer: Defence Technologies, Inc., Turkey
- 6. Naveen Rastogi, Doctor of Philosophy in Aerospace Engineering, February 1995  
Dissertation Title: Load Transfer in the Stiffener-to-Skin Joints of a Pressurized Fuselage  
Initial Employer: Ad Tech Systems Research, Inc., Beavercreek, OH

7. Scott S. Steinbrink, Doctor of Philosophy in Engineering Mechanics, expected October, 1998  
Dissertation Title: Axisymmetric Response of Composite Pressure Domes by the Multiple Shooting Method  
Initial Employer: Gannon University, Mechanical Engineering Department,  
Erie, Pennsylvania
8. José G. Pérez, Doctor of Philosophy in Aerospace Engineering, expected July 1999  
Dissertation Title: Design and Test of Semicircular Composite Frames Optimized for Crashworthiness
9. Darin D. Schultz, Master of Science in Aerospace Engineering, expected October, 1998  
Thesis Title: A Shell-to-Solid Transition Finite Element for Improved Interlaminar Stress Response in Composite Laminates